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Assessment of emission and performance of compression ignition engine with varying injection timing

S.M. Ashrafur Rahman *, H.H. Masjuki, M.A. Kalam, A. Sanjid, M.J. Abedin

Centre for Energy Sciences, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

Engine performance improvement and exhaust emissions reduction are the two most important issues to develop a more efficient engine with less environmental impact. For a diesel engine, injection timing is one of the major parameters that affect the engine performance and emissions. Now-a-days, alternative fuels for internal combustion engines have created interest among the researchers around the world due to the limited reserve and rapid depletion of petroleum based fuels. In this paper, studies focused on characterizing influence of injection timing on engine performance and exhaust emissions have been critically reviewed where diesel, biodiesel, alcohol and other alternative fuels are used. In case of diesel fuel, advancement in injection timing results in lower carbon monoxide (CO) and hydrocarbon (HC) emission; though it increases nitrogen oxides (NO_X) emission. Advance injection timing increases brake thermal efficiency (BTE) and decreases brake specific fuel consumption (BSFC). Biodiesel–diesel blends produce more HC and CO emission, but reduce NO_X emission when injection timing is retarded. Advancement in injection timing results in higher exhaust gas temperature with increase of biodiesel percentage in the blends.

Contents

1. Introduction

Diesel engine is one of the major sources of environmental pollution. The emissions produced due to the operation of diesel engine with diesel are highly responsible for several critical problems. Strict measurements and regulations are being imposed to lower these emissions and improve air quality. In order to

* Correspondence to: Department of Mechanical Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia. Tel.: +60 3 79674448; fax: +60 3 79675317.
E-mail address: rahman.ashrafur.um@gmail.com (S.M.A. Rahman).

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Table 1
Summary of effect of various parameters on engine performance and emission parameters.

Parameters ↓ Factors →	Load	Biodiesel	Torque, compression ratio and injection pressure	Ethanol addition	EGR
Brake specific fuel consumption (BSFC)	Increase in load decreases BSFC [28–31]	Increases in percentages of biodiesel, increases fuel consumption [25,32,33–35] Contrary: Dorado et al. [20] reported biodiesel blends reduced BSFC slightly	Increase in CR decreases BSFC [28,36–38] Increase of injection pressure decreases BSFC [39–41] Contrary: injection pressure increases BSFC [42]		
	BSFC decreases with load when biodiesel is used [25,31,35,43,44]				
Brake thermal efficiency (BTE)	Increased with increase in load [45]	BTE increases with increase in blend percentages [41] Contrary: biodiesel reduces BTE due to having lower heating value and higher viscosity [46–48]	– Increase in torque increases BTE [49] – Increase in compression ratio improves BTE [29] – Injection pressure decreases efficiency [42]	Introduction of ethanol increases BTE [50]	
	BTE improves with load when biodiesel is used [51]				
Exhaust gas temperature (EGT)	Increase in load increases EGT [29,45,53]	BTE increases as biodiesel concentration increases [29]		Increase in ethanol percentages increases EGT [54]	EGR reduces EGT [53,55–57]
Nitrogen oxides (NO_X)	Increase in load increases emission [58,59]	– Biodiesel increases emission [60–73] – Contrary reduces emission [74]	Increase in injection pressure increases emission [75]	– Reduces NO_X emission [76,77] – Contrary increases emission [78]	– Introduction of EGR reduces NO_X [79,80], even when biodiesel is used [81–83]
Hydrocarbon (HC), Carbon monoxide (CO) and Particulate matter (PM)		Biodiesel reduces emission [20–24,26,27,60–73] Contrary: biodiesel increases emission [85,86]	High injection pressure reduces PM emission [87,88]	– Introduction of ethanol Increases HC emission [89] and CO emission [41,89] – Reduces CO emission [90,91] – Reduces CO, HC and soot [92] – Increase in ethanol percentages increases emissions [93,94]	High EGR increases HC emission [95,96]

reduce these emissions, diesel engine performance parameters need to be improved, such as: brake thermal efficiency, brake specific fuel consumption, exhaust gas temperature etc. Various investigations have been performed in order to improve engine performance and emissions. Injection system plays a vital role in reducing engine emissions and improving fuel economy. Based on the injection characteristics, engine performance can be predicted. Injection duration, injection pressure, injection timing, and fueling are the main injection parameters which greatly affect the engine performance and emissions [1,2]. Exhaust gas recirculation [3] helps to attain lower emissions and higher engine performance.

Numerous studies are going on around the world to find potential replacement of petroleum-based fuels. In this regard, investigations of diesel engines using alternative fuels such as biodiesel, ethanol etc. are worthy of exploration [4–9]. Biodiesel is a non-toxic, sulfur-free, oxygenated, biodegradable and renewable fuel source. Another advantage of biodiesel is that it can be used either in pure form or blended with fossil diesel, with a little or without any engine modification. Biodiesel has similar energy density and cetane number, slight sulfur and ample oxygen content compared to fossil diesel fuel [10–15]. However, lower volatility, higher molecular weight and viscosity of biodiesel lead to some critical problems such as injector cooking, severe engine deposits, piston ring sticking etc. [16–19]. Overall, biodiesel provides comparable horse power and fuel efficiency. Many investigations have been carried out on engine exhaust emissions using biodiesel. The results showed lower hydrocarbons, carbon monoxide and particulate matter emissions, but higher nitrogen oxide emission for biodiesel [20–27].

In Table 1, the effect of various factors such as: Load, Biodiesel, Torque, Compression ratio, Injection pressure, EGR, Ethanol addition on engine performance and emission parameters.

In this review paper, the effect of changing the fuel injection timing on engine performance and emission parameters have been reported.

2. Engine performance and emission parameters

2.1. Brake specific fuel consumption (BSFC)

BSFC is a comparison ratio between amounts of fuel the engine uses versus amount of power produced. BSFC is a measurement used to evaluate performance of car engines.

2.2. Thermal efficiency

Thermal efficiency is the ratio of the output or work done by the working substance in the cylinder in a given time to the input or heat energy of the fuel supplied during the same time. Thermal efficiency can be divided into two kinds: indicated thermal efficiency and brake thermal efficiency. The brake thermal efficiency (BTE) indicates how efficiently the energy in the fuel was converted to mechanical output [97].

2.3. Exhaust gas temperature

EGT is the most critical working parameter of a diesel engine, because if excessive EGT makes parts too hot; the expensive parts within or attached to engine start to get welded together or collapse into the exhaust pipe [52].

2.4. Emission parameters

The exhaust from the diesel engine includes a wide range of gaseous and particulate phased organic and inorganic compounds, which contain greater quantities of aromatic and sulfur [98]. Diesel exhaust varies with the operating conditions: (i) Engine type, (ii) Fuel, (iii) Presence of emission control system and (iv) Lubricating oil [3]. Diesel engine pollutants can be classified into nitrogen oxides (NO_X), hydrocarbons (HC), carbon monoxide (CO) and particulate matter [53,84,99,100].

2.5. Nitrogen oxides (NO_X)

Combination of nitric oxide (NO) and nitrogen dioxide (NO_2) is known as Nitrogen oxides or NO_X. They exist on some level in the exhaust. NO_X formation depends upon: (a) Temperature of the cylinder, (b) Time needed for the reaction to take place, (c) Coefficient of air surplus, and (d) In-cylinder temperature [101–104]. There are three mechanisms of NO_X formation: (i) thermal, (ii) prompt and (iii) fuel. The first mechanism "thermal" is also known as Zeldovich Mechanism [105–108]. This mechanism states that, "Nitrogen molecule's triple bond is broken by high combustion temperature (1800 K). Then the nitrogen molecule dissociates into their atomic states and participates in series of reaction with oxygen and produces thermal NO_X". Free radical development in the flame front of hydrocarbon flames leads to fast production of NO_X, recommended by prompt mechanism. In the time of combustion of fuel, NO_X is shaped by the reaction of oxygen with nitrogen bound in the fuel. The complex production process includes 50 in-between species and more than hundred reversible reactions [101].

2.6. Hydrocarbon (HC)

When there is unburned fuel through the engine exhaust, it results in hydrocarbon emissions. HC emissions constitute compounds of hydrogen, carbon, and occasionally oxygen. The two main causes of Hydrocarbon emission in diesel engines are: (a) during the delay period, fuel mixture is leaner than that of the lean combustion limit and (b) under-mixing of fuel. At light or idle load, the more important factor is over-mixing, especially for small size engines operating at high speed [109].

2.7. Particulate matter (PM)

Particulate matter [84] is an air-adjourned mixture of solid and liquid components that vary in: Shape, Surface area, Size, Number, chemical composition, Solubility and Source [110–113]. PM is a highly complex mixture of fine particles and liquid droplets, which includes: Ash, Soot, water Soluble Organic Fraction [114] and HC SOF [84,115–117]. The size distribution includes fine, coarse and ultra-fine particles. These particles exist in different shapes and densities in the air [117].

2.8. Carbon monoxide (CO)

Incomplete oxidation product of hydrocarbon fuel results in carbon monoxide (CO) emission. In fuel-rich combustion products and in the high-temperature burned gas, small amount of CO is present. Fuel/air ratio effectively determines the amount of CO. During combustion when there is chemical equilibrium, slow recombination with oxygen causes CO levels to get a freeze during expansion and exhaust strokes. The CO emission in the exhaust represents lost chemical energy that is not fully utilized [118–120]. As burning declines when reaction temperature is less than 1500 K, CO emission also increases. The OH radical converts CO to CO_2 [121].

Table 2
Effect of injection timing on engine performance parameters: BSFC, BTE and EGT.

Study	Ref	Fuel used	IT	BSFC	BTE	EGT
Raheman and Ghadge	[29]	Mahua biodiesel (B100) and its blends with High speed diesel	Advanced from 35° to 45° before TDC	Mean BSFC decreased by 15.8%	Increase- HSD 12.9% B20 10.1% B40 12% B60 12.3% B80 18% B100 18.1%	Mean EGT reduced by 15.9% Decrease- HSD 15.3% B20 15.4% B40 15.4% B60 16.2% B80 16.5% B100 16.6%
K. Zeng et al	[124]	Natural gas	Advancement from 150 to 180°CA BTDC		Increases from 12% to 26%	
Kumar et al.	[131]	Honge methyl ester	Retarding or advancing by 3°	For B20-Retarding increases BSEC by 5.2% and advancing increases BSEC by 2.9%	– BTE for B20 decreased by 1.15–2.1% – BTE for diesel decreased by. 8–2.3%	Reduction by 2.6% for B20
R. Zhu et al.	[122]	Diesel-dimethoxymethane blends	20 CA BTDC to 26 CA BTDC	Improves BSFC	Improves efficiency	
G. H. Abd Alla et al.	[132]	Dual fuel: diesel mixed with methanol or propane	Advanced injection timing from 25 BTDC to 30 BTDC		Increases BTE	
T. Ganapathy et al.	[129]	Jatropha biodiesel and diesel	Advanced from 340 to 350 CAD	– BSFC of Jatropha biodiesel increases – BSFC of diesel increases with retardation or advancement from rated injection timing (345 CAD)	– Jatropha biodiesel achieves higher efficiency at advanced injection timing (340 CAD) – Diesel fuel achieves higher efficiency at rated injection timing	
Nwafor	[125]	Diesel and net rapeseed oil	Advanced to 33.5° BTDC	Fuel consumption was highest for rapeseed oil	Efficiency was highest for rapeseed oil	EGT increased
C. Sayin et al.	[126]	Diesel and methanol	Advancing the injection timing 5°CA (from 20° to 25°CA BTDC) Retarding the injection timing 5°CA (from 20° to 15°CA BTDC)	 BSFC increased by 30.26% for M15	BTE decreased by 19.45% for M10 BTE decreased by 29.02% for M10.	
Bari et al.	[133]	Waste cooking oil and diesel	Advancing injection timing from 15°CA BTDC to 19 × CA BTDC		BTE increased 1.6%	Increased exhaust temperature
Hariram and Kumar	[128]	Algal Oil Methyl Ester (AOME)	Retardation of injection timing of 5°	Increased	BTE reduced by 3–4%	
A.K. Agarwal et al.	[134]	Diesel fuel	Injection timing advanced	Increased	Increased	Decreased
Y. Wang et al.	[135]	Dimethyl Ether	Injection timing advanced from 3 to 11°CA BTDC	From 3 to 7°CA BTDC BSFC decreased but		

Table 2 (*continued*)

Study	Ref	Fuel used	IT	BSFC	BTE	EGT
				from 7 to 11°CA BTDC BSFC increased		
D. Qi et al.	[136]	Biodiesel produced from soybean oil	Retardation of injection timing	Increased		
Sayin and Canakci	[137]	Ethanol and diesel blend	Retarding injection timing from 27 to 21°CA BTDC	Increased by 47.7% for E15 @30 Nm	BTE decreased by 37% for E10 at 30 Nm	
			Advancing injection timing from 27 to 33°CA BTDC		BTE decreased by 35% for E10 at 30 Nm	
Muralidharan and Govindarajan	[45]	Pongamia Pinnata Methyl Ester	Injection timing advanced	Decreases	Increases	
A. Murcak et al.	[138]	Ethanol and diesel blend	Advanced to 35°CA BTDC	Reduced BSFC		
Mani and Nagarajan	[139]	Waste plastic oil	Retarded to 14°CA BTDC	BSFC varied from 0.574 g/kWh at no load to 10.297 g/kWh at full load for standard injection timing, and it varies from 0.514 g/kWh at no load to 0.235 g/kWh at full load for retarded injection timing.		Varies from 240 °C at no load to 45 °C at full load for standard injection timing and for retarded injection timing, it various from 230 °C at no load to 436 °C at full load
S. Jaichandar et al.	[140]	Pongamia oil Methyl Ester	Retarded from 23 to 21°CA BTDC		Slightly increases BTE	
Balusamy and Marappan	[141]	Thevetia Peruviana seed oil methyl ester	Injection timing advanced		Increases BTE	Variation not significant

3. Effect of injection timing

For a diesel engine, fuel injection timing is a major parameter that affects the combustion and exhaust emissions. When the fuel is injected, the state of air changes with the variation in injection timing, and thus ignition delay will vary. If injection starts earlier, the initial air temperature and pressure will be lower; hence the ignition delay will increase. If injection starts later (when piston is closer to TDC), the temperature and pressure will be slightly higher, and thus a decrease in ignition delay will proceed. Hence, injection timing variation has a strong effect on the engine performance and exhaust emissions, especially on the brake specific fuel consumption (BSFC), brake thermal efficiency (BTE) and NO_X emissions. This is due to changing maximum pressure and temperature in the cylinder.

Several studies suggest that, retarding injection timing reduces NO_X emissions [89,90,122]. As injection timing retardation decreases the peak cylinder pressure which results in lower peak temperatures and thus NO_X emissions diminish [123]. On the contrary, advancement in injection timing decreases CO and HC emissions. Zeng et al. [124] reported that, the volumetric efficiency decreases as fuel injection timing is advanced. Late fuel injection timing largely influences engine performance, combustion and emissions. Retarding injection timing means fuel injection starts later, as a result combustion duration decreases, which results in lower peak cylinder pressure. Therefore, incomplete combustion occurs, due to which BTE decreases and BSFC increases; as lesser output power is produced [41,122]. Nwafor [125] reported that, advanced injection timing produced lowest CO_2 emissions due to early combustion resulting in ash formation, which is a result of high cylinder pressure and temperature. Sayin et al. [126] reported that advancing the injection time results in a decrease in CO emission. This is due to the fact that advanced injection timing increases oxidation process between carbon and oxygen molecule and also produces higher cylinder temperature [127]. Raheman and Ghadge [29] reported the EGT reduced incessantly with advancement of IT, because of the favorable pressure–temperature profile. This produced higher thermal efficiencies as injection timing advanced.

Hariram and Kumar [128] investigated the effect of injection timing on performance, combustion and emission parameters using algal oil methyl ester (AOME) and its blends. Advancement in injection timing resulted reduction in brake specific fuel consumption, unburned hydrocarbon, carbon monoxide and smoke, and increases combustion pressure, rate of heat release, brake mean effective pressure and oxides of nitrogen.

Ganapathy et al. [129] reported that, in case of diesel oil, BSFC increases whether injection timing is advanced or retarded. But, in the case of Jatropha biodiesel operation, BSFC increases when injection timing is varied from advanced to retarded. This is supported by literature [126]. Any change of injection timing from standard timing decreases BTE for diesel. In case of Jatropha,

Table 3
Effect of injection timing on engine exhaust parameters: NO_X, CO, PM and HC.

Study	Ref	Fuel used	IT	NO_X	CO	PM	HC
K. Zeng et al	[124]	Natural gas	Retardation from 170°CA BTDC to 150°CA BTDC	Decreases emissions from 600 PPM to 10 PPM	Constant 0.1% vol emission		Increases emission from 200 PPM to 500 PPM
T. Ganapathy et al.	[129]	Jatropha biodiesel	Advanced from 340 to 350 CAD	For both fuels, retardation causes significant reduction of emissions whereas advancement increases emission	– For diesel fuel, increase or decrease from rated injection timing increase emission – for Jatropha biodiesel, advancement of injection timing has no effect, but retardation increases emission significantly	Advanced timing reduces and retardation increases smoke density for both fuels	Any change from rated ignition timing, retardation or advancement, increases emission for both fuel.
Hariram and Kumar	[128]	Algal Oil Methyl Ester (AOME)	Advancement of injection timing of 5°	Increased	Reduces by 2.5%		Decreased
			Retardation of injection timing of 5°	Reduces by 2.5–3.4%	Increases	Increases	Increases
Muralidharan and Govindarajan	[41]	Pongamia Pinnata Methyl Ester	Injection timing advanced	Increased	Reduced	Reduced	Reduced
S.H. Park et al.	[89]	Ultra low sulfur diesel and diesel–ethanol blends	Retardation	Decreases emission; higher the load, higher the reduction	Increases emission significantly for all the fuels		Increases emission significantly for all the fuels
Kumar et al.	[131]	Honge methyl ester	Retardation or advancement from 27°CA BTDC	Retarding the injection by 3° emission decreased by 4.8% for B20	Advancing the injection by 3° reduces emission by 20% for B20	Advancing the injection by 3° reduces smoke opacity by 4.2% for B20	Advancing the injection by 3° reduces emission by 10% for B20
R. Zhu et al.	[122]	Diesel–dimethoxymethane blends	20 CA BTDC to 26 CA BTDC	Increases emission	Decreases emission	Reduces emission	
G. H. Abd Alla et al.	[132]	Dual fuel: diesel mixed with methanol or propane	Advanced injection timing from 25 BTDC to 30 BTDC	Increases emission	Emission decreases		Reduces emission
Nwafor	[125]	Diesel and net rapeseed oil	Advanced to 33.5° BTDC		Produced lowest emission for rapeseed oil		Produced lowest emission for rapeseed oil
D Qi et al.	[136]	Biodiesel produced from soybean oil	Retardation of injection timing	Reduces emission			
C. Sayin et al.	[126]	Diesel and methanol	Advancing the injection timing 5°CA (from 20° to 25°CA BTDC)		Emission reduced by 17.7% for M10	Decreased by 5.31% for M0	Emission reduced by 20.12% for M10
			Retarding injection timing 5°CA (from 20° to 15°CA BTDC)	Emission reduced by 28.12% for M5	Emission increased by 29.41% for M10		Emission increased by 19.23% for M10

Table 3 (*continued*)

Study	Ref	Fuel used	IT	NO_X	CO	PM	HC
Bari et al.	[133]	Diesel and waste cooking oil	Advancing injection timing from 15°CA BTDC to 19°CA BTDC	Increased emission by 76.6% for WCO and 91.4% for Diesel	Emission reduced by 9.9% for WCO and 44.9% for diesel		
A.K. Agarwal et al.	[134]	Diesel fuel	Injection timing advanced		Decreased emission		Decreased emission
			Retardation of injection timing			Produced highest PM	
Y. Wang et al.	[135]	Dimethyl ether	Injection timing advanced from 3 to 11°CA BTDC	Emission increased significantly	Slightly reduced	Slightly reduced	
Sayin and Canakci	[137]	Ethanol and diesel blend	Advancing timing from 27 to 30°CA BTDC		Emission reduced by 15.5% for E15 @30 Nm and 1800 RPM		
			Retarding injection timing from 27 to 21°CA BTDC	37.3% reduced for E5 at 30 Nm	Emission increased by 59.1% for E15 @30 Nm and 1800 RPM	Emission increased by 51.2% for E15 @30 Nm	
			Advancing timing from 27 to 33°CA BTDC			Decreased by 18.8% for E15 @30 Nm	
Mani and Nagarajan	[139]	Waste plastic oil	Retarded to 14°CA BTDC	NO_X varies from 16.35 g/kWh at no load to 8.9 g/kWh at full load for standard injection timing whereas for retarded injection timing it varies from 14.63 g/kWh at no load to 8.56 g/kWh at full load.	Varies from 17.69 g/kWh at no load to 1.59 g/kWh at full load for standard injection timing, and it varies from 14.49 g/kWh at no load to 7.15 g/kWh at full load		Varies from 0.598 g/kWh at no load to 0.147 g/kWh at full load for standard injection timing, and it varies from 0.314 g/kWh at no load to 0.0336 g/kWh at full load
S. Jaichandar et al.	[140]	Pongamia oil methyl ester	Retarded from 23 to 21°CA BTDC	Decreases emission	Marginal increase		
Balusamy and Marappan	[141]	Thevetia Peruviana seed oil methyl ester	Injection timing advanced	Increased	4° advancement resulted in 25% reduction	6° advancement reduced emission to 38% from 45%	Decreased
Z. Zhu et al.	[142]	Dimethyl Ether (DME)	Retarded by 3 to 6°CA BTDC	Emissions reduced by 20–35%	Slightly increases		
J. Hwang et al.	[143]	Waste cooking oil biodiesel	Retarded from 25 to 0°CA BTDC	Decreased emission	At low load- increases at high load- decreases		

highest BTE was achieved at advanced injection timing. Retarding the injection timing increases the CO emissions with Jatropha biodiesel due to incomplete and late burning.

Buyukkaya and Cerit [130] studied the effects of injection timing on NO_X emissions of a low heat rejection (LHR) turbocharged direct injection diesel engine. To reduce NO_X emissions released by diesel engines, the LHR engine was tested at 18° and 16° crank angle before top dead center (BTDC). Speeds and load conditions were kept constant. The results showed reduction of BSFC and NO_X emissions when injection timing was retarded.

Tables 2 and 3, depict the effect of injection timing on various parameters, such as: brake specific fuel consumption, brake specific energy consumption, brake thermal efficiency and exhaust gas temperature (Table 2) and emissions – Oxides of nitrogen, carbon monoxide, hydrocarbons and particulate matter (Table 3).

4. Conclusion

Fuel injection timing heavily affects the performance of diesel engines and emission as well. In this review, the performance and exhaust emissions of diesel engine at the different injection timings has been reported:

(a) Retarding the injection timing decreases the peak cylinder pressure, which results in lower peak temperatures. As a consequence, the NO_X emissions reduce.
(b) When injection timing is retarded, fuel injection starts later. As a result, combustion duration decreases which results in lower peak cylinder pressure. Therefore, incomplete combustion occurs and BTE decreases and BSFC increases; as lesser output power is produced.
(c) When injection timing is advanced, it ensures complete combustion and results in an increase in BTE.
(d) Advanced injection timing produces higher cylinder temperature and increases oxidation process between carbon and oxygen molecules, thus HC and CO emission decreases.
(e) As cylinder temperature increases with increase in ignition timing, it significantly increases NO_X emission.
(f) Retarding injection timing shows an increase in BSFC, HC, CO and smoke with marginal improvement in combustion pressure, Rate of heat reduction, BMEP and NO_X emission.
(g) Exhaust gas temperature decreases as Injection timing is advanced.
(h) Biodiesel–diesel blends produce more HC and CO emission, but reduce NO_X emission when injection timing is retarded.
(i) The injection advance was found to have increasing effect on EGT with increasing concentration of biodiesel.
(j) The advanced injection resulted in an increase in BTE as a result of the increase in percentage of biodiesel in the blends.

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